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Comparative Life Cycle Assessment of the Conventional Façade SOS Natura and the Natural Water Tank Façade

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HIGHLIGHTS

- Two façades designed for the energy rehabilitation of Spanish commercial buildings.
- LCA methodology used to perform the environmental evaluation of the façades.
- Comparative analysis of the impacts generated to compare environmental behaviour.

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ABSTRACT

The construction industry produces great environmental impacts to the planet. In order to tackle this problem, the European Union has put into effect Regulation No 305/2011, which compels the construction products manufacturers to carry out environmental performance studies of these products and thus make public the impact they cause on the environment. The aim of this research is to make known the environmental impacts of the SOS Natura Conventional Façade (CF) solution, obtained within the research project "SOS Natura, Vegetal Architectural Solutions" developed by the Department of Construction and Technology in Architecture of the School of Architecture of the Technical University of Madrid (Spain). In addition, we report an environmental comparative with the Natural Water Tank Façade (NWTF), studied previously by the same work group and included in the same research project. We present as well an uncertainty analysis for both façades. Following the study conducted we conclude that the NWTF profile has a slightly better environmental behaviour when compared to the CF profile for the entire life cycle in most of the impact categories analysed in this study. However it should also be noted that, in detail and at stage level, the NWTF presents a higher environmental impact than the CF.

1. Introduction

The construction industry is not environmentally friendly, as shown in the many studies performed about the environmental impact of building materials, construction systems and the different construction stages of buildings [1–11].

According to the Worldwatch Institute, construction uses 25% of the lithosphere's resource extraction; it needs over 2 t of raw materials per m^2 of building; the amount of energy associated with the manufacture of the materials used in a building is 1/3 of a family's energy consumption during a period of 50 years and the production of construction and demolition waste exceeds one annual tonne per capita [12].

Given these results, the European Union (EU) has put into effect Regulation No 305/2011 [13], which compels manufacturers of construction products to carry out environmental behaviour studies of these products and thus find out the impact they cause on the environment. This information is collected in product labelling or in the Environmental Product Declarations (EPD) [14], both publicly available documents very useful for the sector's professionals, since with this information they can prescribe the product or building system most suitable for the project, taking into account both its technical and environmental characteristics.

The study analysed in this article is included within the research project "SOS Natura, Vegetal Architectural Solutions", whose main aim has been the development of the façade systems SOS Natura Conventional Façade (CF) and Natural Water Tank Façade (NWTF) [15], which improve the thermal envelope and energy efficiency of the building throughout its life cycle.

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In this report we analyse the environmental impacts generated by the CF system and compare them to the impacts obtained in the Life Cycle Assessment study of the NWTF, so that we can observe which of the two systems has a better environmental behaviour. Following this comparative, we present an uncertainty analysis for both the CF and the NWTF.

2. Materials and methodology

We have used the Life Cycle Assessment (LCA) methodology to obtain the environmental impacts associated with the CF system. With this study we have been able to compare the environmental impacts associated with each impact category analysed in both solutions. The information obtained will help the firm that markets them, Intemper S.L., to inspire environment improvement actions of both products.

The methodology used follows the recommendations and complies with the requirements of the international standards ISO 14040:2006 [16] and ISO 14044:2006 [17]. Similarly, we have followed the recommendations of standard EN 15804:2012 [18] so that the results of the study may be used in the development of an Environmental Product Declaration (EPD).

2.1. Objectives and scope of the study

The aim of the study is the analysis and assessment of the environmental impacts associated with the production of the CF for its later comparison with the environmental impacts associated with the production of the NWTF, previously studied [15].

2.1.1. Scope of the study

In Fig. 1 we can note the enclosure system CF composed of a sandwich panel with insulation, a half brick thick leaf and a layer of setting coat. This enclosure will also have a steel structure, made of a vertical sub-structure and brackets. In Fig. 2 we can note the enclosure system NWTF, made of: panels composed of independent modules with vegetation (NATURPANEL® Water Tank, referred to as container throughout this article); layer or substrate feeding the vegetation; waterproofing and insulation core; structural support and interior finishing that waterproofs everything as a whole. The modules measure 60 cm × 60 cm × 8 cm, with the necessary substrate inside for the development of the plant species, and adding a reservoir for the storage of water and nutrients, to each panel. Both enclosures comply with the hygrothermal and acoustic requirements of the Spanish Technical Building Code [19], regarding their function as a façade. Table 1 shows all the components associated with the solutions proposed for the CF and NWTF envelopes.

The functional unit proposed for both enclosure systems is "1 m^2 opaque vertical enclosure, intended for buildings used for the service sector and with a duration of 40 years".

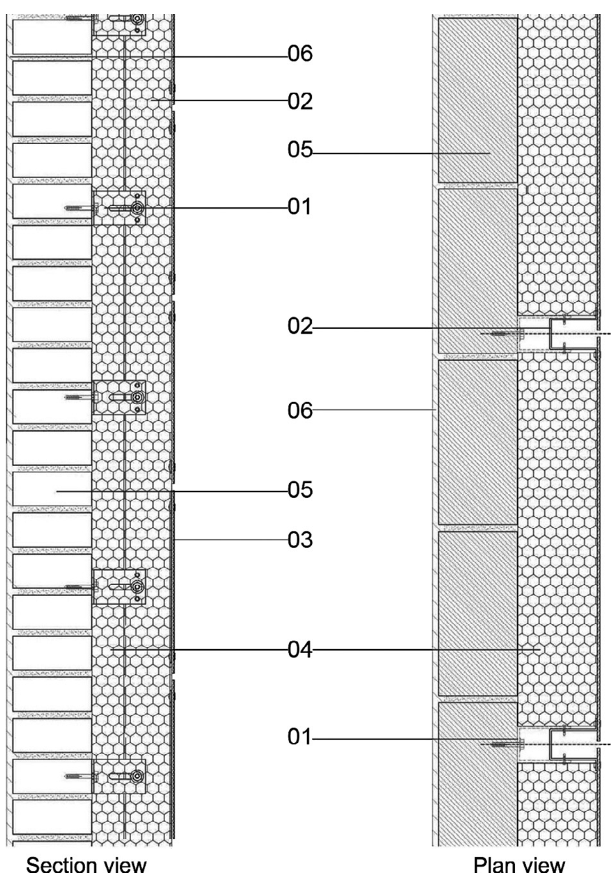

Fig. 1. Plan and section views corresponding to the enclosure system of the Conventional Façade (CF).

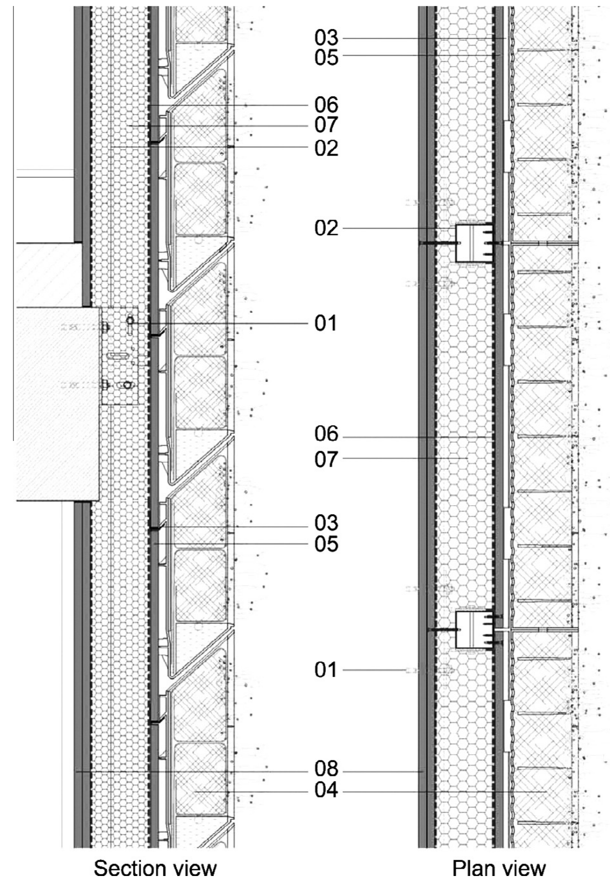

Fig. 2. Plan and section views corresponding to the enclosure system of the Natural Water Tank Façade (NWTF).

2.1.2. System restrictions

The system restrictions include the following stages of the analysed façades' life cycle:

Table 1
Components associated with the proposed solutions: CF and NWTF.

Façade	Layers	Code	Description
CF	Metal structure	01	Brackets
		02	Vertical substructure
	Exterior enclosure	03	Sandwich panel
	Intermediate enclosure	04	Insulation
	Interior enclosure	05	Half brick thick leaf
		06	Setting coat
NWTF	Vegetation	01	Modules with vegetation
	Metal structure	02	Brackets
		03	Vertical substructure
		04	Horizontal substructure
	Exterior enclosure	05	Cement board
	Intermediate enclosure	06	Waterproof sheet
		07	Insulation
	Interior enclosure	08	Laminated plasterboard

Table 2
Inventory (data) components of CF and NWTF.

Façade	System	Element	Material	Manufacture of the product					Transport	End-of-life process	
				Material per container (kg)	Material/functional unit (kg)	Amount/FU	Contribution (%)	Transport (distance km)	Transport (distance km)	End-of-life process	Waste processing
CF	Metal structure	Brackets	Laminated steel	–	0.62	2.78 ud	0.43	–	Lorry 20–26T (100)	Recycling	–
		Fixing bolts	Stainless steel AISI 304	–	0.04	2.78 ud	0.03	–	Lorry 20–26T (100)	Recycling	–
		Mullion and muntin	Laminated steel	–	4.83	1.67 m	3.32	–	Lorry 20–26T (100)	Recycling	–
		Fixing screws	Stainless steel AISI 304	–	0.01	5.56 ud	0.01	–	Lorry 20–26T (100)	Recycling	–
	Layers	Sandwich panel	Aluminium and LDPE	–	5.5	1 m^2	3.78	–	Lorry 34–40T (500)	Rubbish tip	Aluminium. LDPE
		Metal rivet	Stainless steel AISI 304	–	9.54E−03	6.68 ud	0.01	–	Lorry 7T (50)	Rubbish tip	Steel
		Insulation	Stone wool insulation	–	4.8	1m^2	3.3	–	Lorry 34–40T (100)	Rubbish tip	Mineral wood
		Brick wall	Perforated brick	–	76.83	57 ud	52.75	–	Lorry 20–26T (50)	Rubbish tip	Inert material (not specified)
			Cement mortar	–	42	–	28.84	–	Lorry 20–26T (50)	Rubbish tip	Inert material (not specified)
		Setting coat	Plaster	–	1.10E+01	1 m^2	7.55	–	Lorry 20–26T (50)	Rubbish tip	Inert material (not specified)
NWTF	Vegetated layers	Vegetation	Depending upon location project	1.50E+00	15.37	–	14.26	–	Lorry 20–26T (200)	–	–
		Vegetable substrate	Substrate with coconut fibre (70%)	1.76E+00	18.01	–	16.71	Ship/Lorry 34–40T (12000/1000)	Lorry 34–40T (500)	Rubbish tip	Organic waste
			EPS (30%)	7.46E−01	7.64	–	7.09	Lorry 34–40T (50)	Lorry 34–40T (500)	Rubbish tip	Plastic mixtures
			NPK fertilizers (1%)	2.53E−02	0.26	–	0.24	Lorry 34–40T (1200)	Lorry 34–40T (500)	–	–
		Synthetic filter Feltemper®150	Polyester textured filament	1.11E−01	1.14	–	1.06	Lorry 20–26T (50)	Lorry 34–40T (500)	Rubbish tip	Plastic mixtures
		NATURPANEL Water Tank (container)	Polypropylene (10% talcum)	1.31E+00	13.37	–	12.41	Lorry 34–40T (300)	Lorry 34–40T (500)	Recycling	Plastic mixtures
			Colorants additives RAL 6006 (1.5%)	1.96E−02	0.2	–	0.19	Lorry 7T (300)	Lorry 34–40T (500)	–	–
		Synthetic filter Feltemper®150	Polyester textured filament	3.10E−02	0.32	–	0.29	Lorry 20–26T (50)	Lorry 34–40T (500)	Rubbish tip	Plastic mixtures
		Separating film	Polycarbonate	1.80E−02	0.18	–	0.17	Lorry 7T (50)	Lorry 34–40T (500)	Rubbish tip	Plastic mixtures
		Water supply	Rubber	3.00E−03	0.03	–	0.03	Lorry 7T (50)	Lorry 34–40T (500)	Rubbish tip	Plastic mixtures
	Metal structure	Branckets	Laminated steel	–	0.7	1.233 ud	0.65	–	Lorry 20–26T (100)	Recycling	–
		Fixing bolts	Stainless steel AISI 304	–	0.009	2.47 ud	0.08	–	Lorry 20–26T (100)	Recycling	–
		Mullion	Laminated steel	–	6.29	1.67 m	5.84	–	Lorry 20–26T (100)	Recycling	–
		Fixing screws brackets	Stainless steel AISI 304	–	0.02	1.233 ud	0.02	–	Lorry 20–26T (100)	Recycling	–
		Muntin	Cold formed steel	–	2.24	3.33 m	2.07	–	Lorry 20–26T (100)	Recycling	–
		Fixing screws mullion	Stainless steel AISI 304	–	0.01	11.12 ud	0.01	–	Lorry 20–26T	Recycling	–

(*continued on next page*)

Table 2 (*continued*)

Façade	System	Element	Material	Manufacture of the product					Transport	End-of-life process	
				Material per container (kg)	Material/functional unit (kg)	Amount/FU	Contribution (%)	Transport (distance km)	Transport (distance km)	End-of-life process	Waste processing
									(100)		
	Layers	Cement panels	Cement, arid light, fiberglass	–	15.8	1 m^2	14.66	–	Lorry 34–40T (500)	Rubbish tip	Inert material (not specified)
		Joint strips	Polyethylene foam	–	2.97E−03	3.33 m	0	–	Lorry 7T (100)	Rubbish tip	Plastic mixtures
		Fixing screws mullion	Stainless steel AISI 304	–	6.01E−03	6.68 ud	0.01	–	Lorry 7T (100)	Rubbish tip	Steel
		Insulation	Stone wool insulation	–	3.6	1 m^2	3.34	–	Lorry 34–40T (100)	Rubbish tip	Mineral wood
		Waterproof sheet	High density polyethylene	–	0.06	1 m^2	0.06	–	Lorry 20–26T (100)	Rubbish tip	Plastic mixtures
		Laminated plasterboard	Gypsum	–	22.4	2 m^2	25.99	–	Lorry 34–40T (100)	Rubbish tip	Inert material (not specified)
		Fixing screws mullion	Stainless steel AISI 304	–	2.03E−02	6.68 ud	0.02	–	Lorry 7T (100)	Rubbish tip	Steel

A. Distribution of raw and auxiliary materials
B. Transport to factory
C. Manufacture
D. Transport to work site
E. End-of-life (transport and end-of-life process).

As for the processes, the production of machinery and industrial equipment are left out of the system analysed, due to the difficulty implied by taking an inventory of all the goods involved. Moreover, the LCA community considers their environmental impact per product unit to be low, relative to the rest of processes included. We have therefore used several databases where said processes are not included. Those databases, taking into account these processes, have been adapted in order to comply with this criterion. We have not included in the study the packaging of the raw materials nor the packaging of the final product, due to the difficulty of their modelling as it was an addition of several components with different origins until their reception in the construction site.

2.1.3. Criteria for the inclusion of input and output

As for the input and output, we have included in the study all those of which we had information about the amount and type of material. We guarantee that those not included, due to a lack of information about the material, add up to 1% at most of the total amount of material and energy inventoried per functional unit. The sum of all the input and output not inventoried doesn't exceed 4% of the total value, both in material and in energy. The criterion for the exclusion of the input and output complies with Section 6.3.5 of standard UNE-EN 15804.

2.1.4. Hypothesis

During the development of the inventory of the CF we have used data provided by Intemper S.L., regarding the composition and amount of part of the materials and products used, as well as the distances to the suppliers. For the information not provided by the firm, we have considered the same hypotheses we used for the NWTF inventory, explained below:

(1) In order to take inventory of the environmental burdens associated with the materials and processes involved in both solutions of the envelope, we have used the following databases through the GaBi 4.4 software [20]: European Life Cycle Database (ELCD v.1.0.1) [21], Ecoinvent 2.0 [22], and PE International [23].
(2) When considering the environmental impacts generated by the production of the electricity consumed in the system studied, we have taken into account the Spanish electricity mix of 2011, calculated from data provided by the World Wildlife Fund (Observatorio de la Electricidad, Spain) [24].
(3) For road transport in Spanish territory, European territory and worldwide, we have considered three vehicle types: a two axle rigid lorry with a capacity up to 7.5 t, and articulated lorries up to 26 t and 40 t; we have assumed that they all comply with the standard Euro III [25]. For sea transport we have chosen a transoceanic container freighter. For transport to the end-of-life stage we have assumed that there is a construction solid waste tip within an 80 km radius around the building.
(4) We suppose that the components of the CF solution have the same reference operating life than the NWTF ones, which enables them to fulfil their function during the lifetime of the building, established at 40 years.
(5) For the end-of-life processes, we have considered that the impacts derived from the recycling operations have to be attributed to the product systems that use them as raw materials. However all the processes related to depositing in the tip the materials used for the façade, using for this end both the Ecoinvent and the PE International databases, are attributed to the system studied. The Ecoinvent processes regarding the end-of-life of materials include transport to tip, which doesn't happen for those of PE International. In order to maintain the coherence in the use of the databases we have adapted the Ecoinvent processes so that they don't include said phase. This stage of the life cycle has been included in the analysis as a separate process.

2.2. Life Cycle Inventory (LCI) assessment

2.2.1. Raw materials supply, transport, production and transport to the work site

The CF is composed of two systems: the steel structure and the enclosure layers. The NWTF is divided in three systems: the vegetated layer, the steel structure and the enclosure layers.

Table 2 corresponds to specific data provided by Intemper S.L., except the transport to the work site, for which we have considered an average distance scenario of 500 km for Spain. Data regarding the amounts of material have been obtained by measuring the weight of the components in the Intemper S.L. facilities.

The amounts of materials (screws, corbels, metres of mullion or muntin, etc.) are expressed in units per functional unit.

Table 3
Impact categories assessment associated with the supply of raw materials, transportation and manufacture CF.

Methodology	Category	Indicator	Total	Metal structure		Layers	
				kg	%	kg	%
CML 2001	AD	Sb-eq.	8.88E−01	1.08E−01	12.2	7.80E−01	87.8
	A	SO_2-eq.	5.44E−01	6.16E−02	11.3	4.82E−01	88.7
	Eu	PO_4-eq.	5.73E−02	7.83E−03	13.7	4.94E−02	86.3
	GW	CO_2-eq.	1.33E+02	1.35E+01	10.2	1.19E+02	89.8
	O	R11-eq.	7.60E−06	2.39E−07	3.1	7.36E−06	96.9
	PhO	C_2H_4-eq.	6.18E−02	1.03E−02	16.7	5.14E−02	83.3
	HT	DC-eq.	5.95E+01	3.00E+01	50.5	2.94E+01	49.5
	FWAE	DC-eq.	7.89E−01	1.10E−01	13.9	6.79E−01	86.1
	MWAE	DC-eq.	2.00E+05	4.88E+03	2.4	1.95E+05	97.6
Eco-indictor 99	A/E	PDF·m2·a	1.92E+00	2.61E−01	13.6	1.65E+00	86.4
	E	PDF·m2·a	3.60E+00	1.81E+00	50.2	1.79E+00	49.8
	C	DALY	1.90E−05	9.42E−07	4.9	1.81E−05	95.1
	CC	DALY	2.73E−05	2.81E−06	10.3	2.45E−05	89.7
	OLD	DALY	8.00E−09	2.52E−10	3.2	7.75E−09	96.8
	IR	DALY	2.09E−07	1.63E−08	7.8	1.92E−07	92.2
	RI	DALY	8.05E−05	1.58E−05	19.7	6.47E−05	80.3
	RO	DALY	7.45E−08	6.06E−09	8.1	6.84E−08	91.9
	FF	MJ	1.54E+02	9.00E+00	5.8	1.45E+02	94.2
	M	MJ	4.11E−01	3.60E−01	87.5	5.13E−02	12.5

Table 4
Impact categories assessment associated with the transportation to work site CF.

Methodology	Category	Indicator	Total	Metal structure		Layers	
				kg	%	kg	%
CML 2001	AD	Sb-eq.	5.63E−03	1.21E−04	2.2	5.51E−03	97.8
	A	SO_2-eq.	5.14E−03	1.11E−04	2.2	5.03E−03	97.8
	Eu	PO_4-eq.	8.87E−04	1.91E−05	2.2	8.68E−04	97.8
	GW	CO_2-eq.	8.33E−01	1.80E−02	2.2	8.15E−01	97.8
	O	R11-eq.	1.58E−09	3.42E−11	2.2	1.55E−09	97.8
	PhO	C_2H_4-eq.	4.17E−04	8.99E−06	2.2	4.08E−04	97.8
	HT	DC-eq.	2.71E−02	5.84E−04	2.2	2.65E−02	97.8
	FWAE	DC-eq.	9.52E−04	2.05E−05	2.2	9.32E−04	97.8
	MWAE	DC-eq.	1.48E+01	3.18E−01	2.2	1.44E+01	97.8
Eco-indictor 99	A/E	PDF·m2·a	3.88E−02	8.38E−04	2.2	3.80E−02	97.8
	E	PDF·m2·a	6.43E−04	1.39E−05	2.2	6.29E−04	97.8
	C	DALY	1.12E−08	2.41E−10	2.2	1.09E−08	97.8
	CC	DALY	1.74E−07	3.76E−09	2.2	1.71E−07	97.8
	OLD	DALY	1.67E−12	3.59E−14	2.2	1.63E−12	97.8
	IR	DALY	4.15E−11	8.95E−13	2.2	4.06E−11	97.8
	RI	DALY	7.33E−07	1.58E−08	2.2	7.17E−07	97.8
	RO	DALY	4.05E−10	8.74E−12	2.2	3.97E−10	97.8
	FF	MJ	1.33E+00	2.86E−02	2.2	1.30E+00	97.8
	M	MJ	3.60E−05	7.77E−07	2.2	3.52E−05	97.8

With the values of the calculated volume and with data about the materials density, we have been able to determine the mass per functional unit of the components. We also show the percentage in weight of the component in relation to the total weight of the functional unit, both for the CF and the NWTF.

2.2.2. End-of-life: transport and end-of-life process

For the modelling of the end-of-life processes of the materials related to both façades, we have created two groups of materials. On one hand, those for which an important market related to their recycling exists, and on the other hand, those very likely to end up in the tip (Table 1).

The recycled components group includes all the elements from the steel structure, for both the CF and the NWTF, since the materials have a high economic value in the recycling market. We have included in this group the container, large enough to facilitate its separation and guarantee the profitability of its recycling. Currently recycling plastic is a common practice; in fact the polypropylene with which the contained is made has this origin.

The group of materials destined to the tip includes those for which a waste processing does not exist presently. This group includes the fixing screws of the gypsum panels, as well as all the plastic materials that go with the container. We have modelled these elements with an end-of-life in tip even though they're made with recyclable materials, since their dimensions are small which affects the profitability of the recycling operations and the probability of their separation during the demolition of the building. We have modelled the transport of the materials to the tip by a 20–26 t class Euro III lorry, with an 80 km itinerary.

2.3. Impact categories

The impact categories assessed in this work correspond to the CML 2001 [26] and Eco-indicator 99 [27] methodologies, which represent the state of the art of endpoint and midpoint methodologies. For their calculation we have used the GaBi 4.4 software developed by PE International.

The impact categories analysed according to the CML 2001 methodology are:

– Abiotic depletion (AD) (kg Sb equivalents)
– Acidification (A) (kg SO_2 equivalents)
– Eutrophication (Eu) (kg PO_4 equivalents)
– Global warming (GW) (kg CO_2 equivalents)
– Ozone layer depletion (O) (kg R_{11} equivalents)
– Photochemical oxidation (PhO) (kg C_2H_4)
– Human toxicity (HT) (kg 1.4-DB equivalents)

Table 5
Impact categories assessment associated with the end-of-life CF.

Methodology	Category	Indicator	Total	Steel		Aluminium		Mineral wood		Inert material		Plastic mixtures	
				kg	%	kg	%	kg	%	kg	%	kg	%
CML 2001	AD	Sb-eq.	1.06E−02	7.39E−07	0.01	2.03E−04	1.9	4.11E−04	3.9	9.60E−03	90.7	3.71E−04	3.5
	A	SO_2-eq.	1.15E−02	8.26E−07	0.01	2.27E−04	2.0	2.53E−04	2.2	1.07E−02	93.5	2.65E−04	2.3
	Eu	PO_4-eq.	4.08E−02	9.56E−08	0.00	2.63E−05	0.1	5.02E−05	0.1	1.42E−03	3.5	3.94E−02	96.3
	GW	CO_2-eq.	2.91E+00	1.08E−04	0.00	2.97E−02	1.0	3.39E−02	1.2	2.60E+00	89.4	2.46E−01	8.5
	O	R11-eq.	4.05E−08	1.66E−12	0.00	4.55E−10	1.1	1.01E−08	24.9	2.16E−08	53.3	8.36E−09	20.6
	PhO	C_2H_4-eq.	1.85E−03	1.05E−07	0.01	2.87E−05	1.5	4.13E−05	2.2	1.70E−03	92.0	7.86E−05	4.2
	HT	DC-eq.	7.63E−02	4.76E−06	0.01	1.31E−03	1.7	3.09E−03	4.1	6.21E−02	81.4	9.76E−03	12.8
	FWAE	DC-eq.	1.16E−02	1.48E−07	0.00	4.05E−05	0.3	2.46E−04	2.1	6.60E−03	56.8	4.74E−03	40.8
	MWAE	DC-eq.	3.35E+02	2.40E−02	0.01	6.57E+00	2.0	2.60E+00	0.8	3.12E+02	93.2	1.37E+01	4.1
Eco-indictor 99	A/E	PDF·m2·a	6.21E−02	4.43E−06	0.01	1.22E−03	2.0	1.74E−03	2.8	5.75E−02	92.6	1.67E−03	2.7
	E	PDF·m2·a	1.26E−02	9.57E−08	0.00	2.62E−05	0.2	4.62E−04	3.7	1.13E−02	90.0	7.72E−04	6.1
	C	DALY	5.43E−08	2.40E−12	0.00	6.61E−10	1.2	9.18E−10	1.7	3.77E−08	69.3	1.51E−08	27.8
	CC	DALY	5.67E−07	2.25E−11	0.00	6.19E−09	1.1	7.04E−09	1.2	5.07E−07	89.5	4.60E−08	8.1
	OLD	DALY	4.26E−11	1.74E−15	0.00	4.78E−13	1.1	1.06E−11	24.9	2.27E−11	53.4	8.78E−12	20.6
	IR	DALY	6.63E−10	4.40E−14	0.01	1.21E−11	1.8	2.30E−11	3.5	5.73E−10	86.3	5.54E−11	8.4
	RI	DALY	4.13E−06	3.05E−10	0.01	8.39E−08	2.0	4.35E−08	1.1	3.96E−06	95.9	4.30E−08	1.0
	RO	DALY	2.72E−09	1.42E−13	0.01	3.88E−11	1.4	7.03E−11	2.6	2.46E−09	90.5	1.49E−10	5.5
	FF	MJ	2.42E+00	1.69E−04	0.01	4.65E−02	1.9	9.49E−02	3.9	2.20E+00	90.7	8.45E−02	3.5
	M	MJ	1.39E−04	2.73E−09	0.00	7.52E−07	0.5	4.81E−05	34.7	3.54E−05	25.5	5.45E−05	39.3

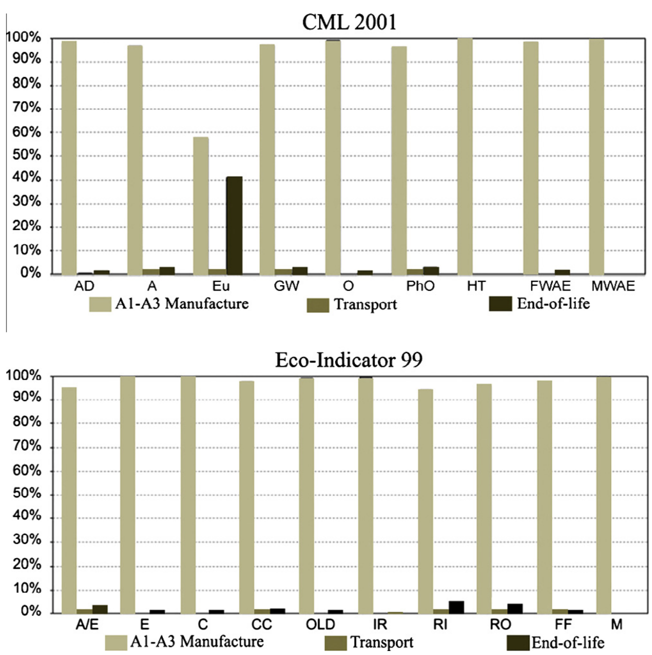

Fig. 3. Relative contribution of the stages analysed in the life cycle associated with the total impact categories (CML 2001 and Eco-indicator 99) of the SOS Natura Conventional Façade (CF).

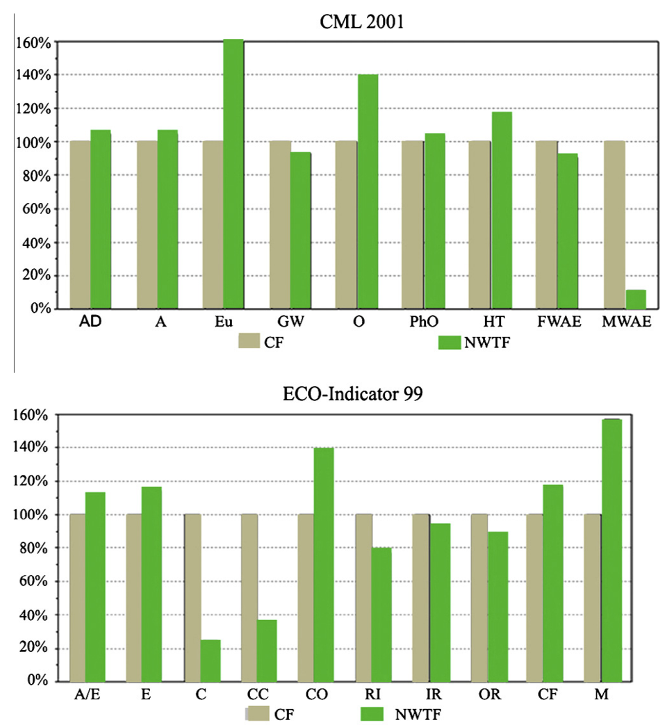

Fig. 4. Comparative of the total impact categories (CML 2001 and Eco-indicator 99) of the SOS Natura Conventional Façade (CF) and the Natural Water Tank Façade (NWTF).

– Fresh water aquatic ecotoxicity (FWAE) (kg 1.4-DB equivalents)
– Marine water aquatic ecotoxicity (MWAE) (kg 1.4-DB equivalents).

The impact categories analysed according to the Eco-indicator 99 are:

– Human Health: carcinogens (C), respiratory organics (RO), respiratory inorganics (RI), climate change (CC), ozone layer depletion (OLD) and ionising radiation (IR). All of them are expressed in Disability Life Years (DALY) [28].
– Ecosystem Quality: ecotoxicity (E) and acidification/eutrophication (A/E). Expressed as Potentially Disappeared Fraction (PDF).
– Resources: minerals (M) and fossil fuels (FF). Expressed as MJ.

3. Impact assessment and interpretation of the SOS Natura Conventional Façade

3.1. Raw materials supply, transport and production

Table 3 shows the impacts due to the raw materials supply, transport and manufacture stage, according to the CML 2001 and Eco-indicator 99 methodologies, of the CF.

Table 6
Uncertainty analysis of the input parameters expressed as percentage of the base value for the CF and the NWTF.

Façade	System	Parameter	Uncertainty (%)
CF	Metal structure	Profiles of metals	5
		Fixing screws	10
	Layers	Aluminium panels	15
		Metal rivet	10
		Insulation	5
		Brick wall	10
		Cement mortar	10
		Setting coat	10
	Transport A4–C2	Transport to work site	20
		Transportation to the rubbish tip	15
NWTF	All system	Service life vegetated layer	50
	Vegetated layer	Plants	10
		Coconut fibre	10
		EPS	10
		Fertilizers	10
		Synthetic filter substrate	10
		Polypropylene chippings (container)	2
		Auxiliary filter	10
		Polycarbonate film	10
		Rubber tubes (water supply)	5
	Metallic structure	Profiles of metals	5
		Fixing screws	10
	Layers	Cement panel	15
		Polyethylene foam	10
		Fixings cement panels	10
		Insulation	5
		Lamina PE Barrera vapour	5
		Plasterboard	5
		Fixing plasterboard	10
	Transport A2/A4/C2	Plants	20
		Coconut fibre (ship)	10
		Coconut fibre (lorry)	10
		EPS	10
		Fertilizers	5
		Synthetic filter substrate	15
		Polypropylene chippings (container)	5
		Auxiliary filter	15
		Transport to work site	20
		Transportation to the rubbish tip	15

3.2. Transport to work site

Table 4 shows the assessment of the impact categories associated with the transport of the CF elements to the construction site of the building stage, according to the CML 2001 and Eco-indicator 99 methodologies respectively.

3.3. End-of-life: transport and final disposal

Table 5 shows the assessment of the impact categories associated with the end-of-life processes of the materials associated with the CF, according to the CML 2001 and Eco-indicator 99 methodologies, respectively. These impacts are broken down into the groups of materials with equal behaviour in the tip. We include in each group the transport to the tip and disposal stage. Additionally, we include in both methodologies the relative contribution to the total impact of each one of the material groups according to their behaviour in the tip. We verify that one of the greatest contributions to the impacts during this life cycle stage comes from the inert materials consisting of the bricks, cement and gypsum. Another important contribution is due to the plastic materials, whose origin is the polyethylene of the sandwich panels and the mineral wool.

4. Results and discussion

4.1. Total results of the SOS Natura Conventional Façade

Fig. 3 shows, by way of summary, the impact categories according to both methodologies used and for each one of the stages analysed. We can observe how the transport to the work site stage and the end-of-life stage barely present any contribution in all the impact categories analysed and in both methodologies. However, we must note that the presence of plastic materials, serves to increase the percentage of impacts associated with the end-of-life stage up to 40% in eutrophication. This value is associated to the elemental flows of COD, ammonium, nitrate and nitrite generated in a mixed plastics rubbish tip treatment, that affect said impact category.

4.2. Comparative assessment of the associated impact categories between the SOS Natura Conventional Façade and the Natural Water Tank Façade

Once we have obtained the environmental impact assessment of the SOS Natura Conventional Façade (CF), we perform the comparative assessment with the data previously gathered in the environmental impact assessment of the Natural Water Tank Façade (NWTF) [11]. Fig. 4 shows the impact categories analysed in both façades, according to both the methodologies used. We assign the reference value to the CF, which is why its bars always have a value of 100% for all the impact categories.

For the CML 2001 methodology, the NWTF presents a greater contribution in the impact categories about eutrophication (186%), stratospheric ozone (139%) and human toxicity (116%), whereas the contribution decreases in marine water aquatic ecotoxicity (11%).

For the Eco-indicator 99 methodology, the NWTF presents a greater contribution in the impact categories related to minerals (157%) and ozone layer depletion (139%), and a lesser contribution for the carcinogens (25%) and climate change (36%) categories.

4.3. Uncertainty analysis

We have carried out the uncertainty analysis for both the CF and the NWTF, for the stages analysed A1–A3, A4 and C2–C4 and for the impact categories of the CML 2001 methodology. The CML 2001 impact categories are the ones with the greater consensus at a scientific and standard level and, with the exception of those related to human toxicity and water aquatic ecotoxicity, they appear in the standard EN 15804 about Environmental Product Declarations and Product Category Rules (PCR) [18].

For the uncertainty analyses we have used the Monte Carlo method, which carries out n simulations on the model made for the calculation of the LCA, introducing random values for each and every one of the input parameters. The random values for these input parameters have to be chosen within the uncertainty limits considered for said parameters [29].

In this work we have carried out 100 simulations considering equal probability distributions and considering the uncertainty limits shown in Table 6. The limits in the uncertainty associated with the final result, that is, associated with the value of the impacts, are calculated for a 95% confidence interval.

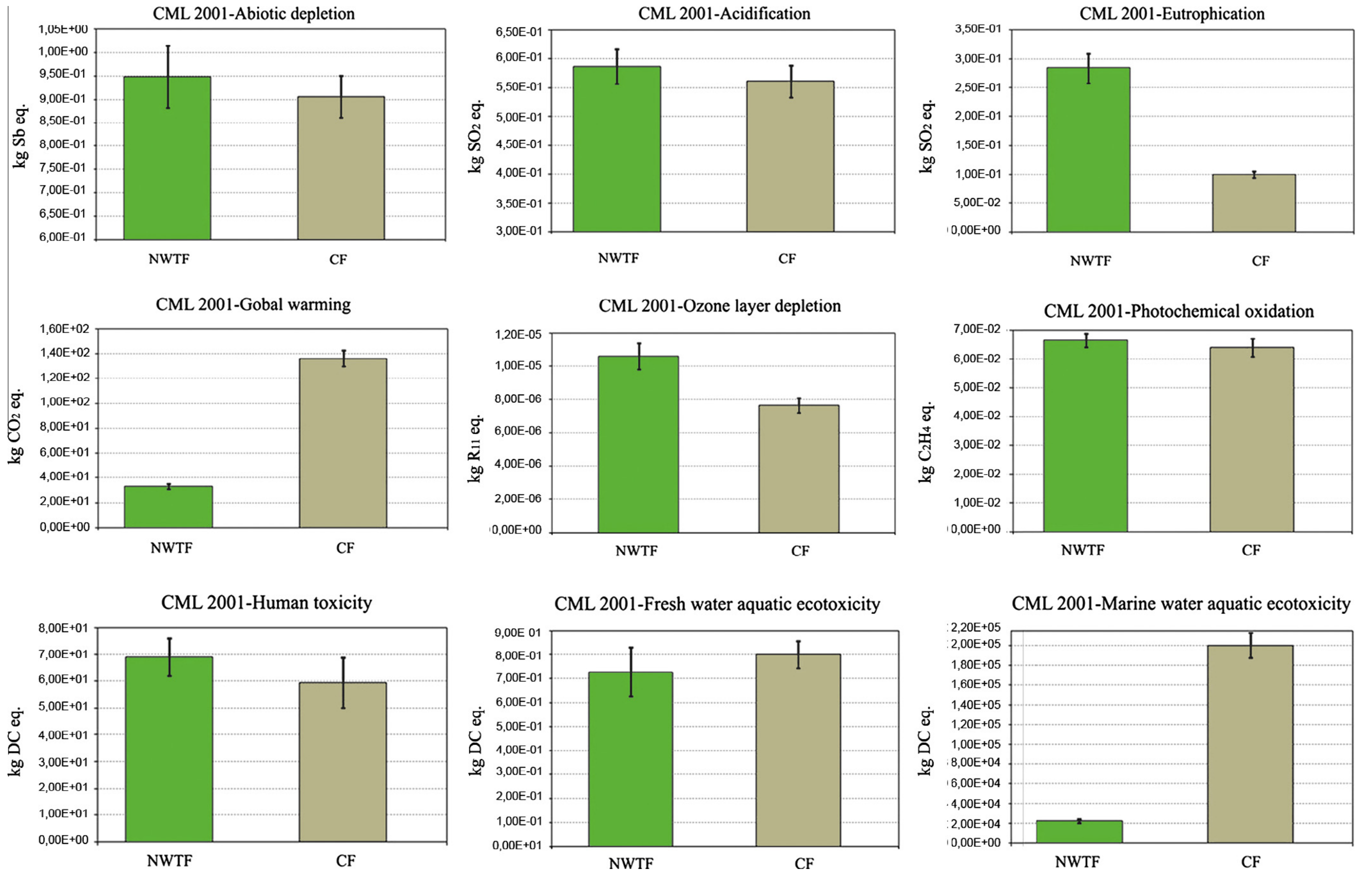

Fig. 5. Comparison between scenarios of the CF and the NWTF (A1–A3/A4/C2–C4).

Fig. 5 show the impact values for the stages A1–A3, A4 and C2–C4 of the NWTF and the CF. These values are shown with the confidence interval calculated in the uncertainty analysis (95%).

5. Conclusions

Following the study carried out, we reach the conclusion that the profile of the NWTF has a slightly better environmental behaviour when compared with the CF for all the life cycle and in most of the impact categories analysed in this study.

Regarding total impacts and in the categories associated with the CML 2001 methodology, the NWTF presents a better behaviour than the CF (taking into account that the CF has a 100% in all the impact categories) in ozone layer depletion, abiotic depletion, acidification, photochemical oxidation and fresh water aquatic ecotoxicity, all these being at least 97%. For global warming it would decrease to 92%. However, the same is not true for human toxicity, slightly higher than for the CF (104%). The only important differences occur for marine water aquatic ecotoxicity (71%) and eutrophication (135%).

As for the impact categories associated with the Eco-indicator 99 methodology, the NWTF presents the same impacts as the CF, for acidification-eutrophication and for ozone layer depletion; for ionising radiation and respiratory organics and inorganics, it doesn't go below 97% (taking into account, again, that the CF has a 100% value in all the impact categories). For climate change it goes down to 92%.

The most notable and significant values occur in the impacts related to carcinogens, which present a 55% reduction in the NWTF (in comparison with the CF), and in the impacts related to minerals, whose increase in the NWTF is quite substantial (145%).

By analysing the impacts in a detailed manner and at a stage level, we reach the following conclusions:

(1) The production stages (A1–A3) present higher impacts in the NWTF, in comparison with the CF, with both the CML 2001 and the Eco-indicator 99 methodologies. This higher contribution is due to the vegetated layer formed by the NATURPANEL® Water Tank container and the steel structure, although it is noteworthy that the highest impact contribution is attributed to the NATURPANEL® Water Tank container, due to the injection process.

(2) The transport to the construction site stage (A4) is the one presenting the lesser contribution to all the life cycle analysed, and can be considered negligible for all the impact analysed, even facing the manufacture of the façade components stages (A1–A3).

Regarding the benchmarking between façades, this stages presents higher impacts for the NWTF in comparison with the CF, even though the total weight of the latter is greater. This is due to the fact that many of the components of the NWTF have to be transported from the Intemper S.L. facilities, increasing the total distance of the shipping.

(3) The end-of-life stages (C2–C4) present, for most of the impacts, a very small contribution to the impact of all the life cycle. In the case of the NWTF, the only impacts of the end-of-life stages that contribute significantly, in relation to the stages A1–A3, are eutrophication, global warming and photochemical oxidation, for the CML 2001 methodology.

Specifically, in the case of eutrophication, the impacts of the end-of-life stages exceed the impacts of the manufacture stages (A1–A3); for global warming and photochemical oxidation, their contribution is of the same magnitude in the manufacture stages. For the impacts associated with the Eco-indicator 99 methodology, and also for the NWTF, the end-of-life stages contribute significantly to carcinogens, climate change and respiratory organics.

In the case of the CF, the only significant impact associated with the end-of-life stages is eutrophication (CML 2001 methodology).

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